Hadronic Dark Matter Searches at CMS at $\sqrt{s} = 13$ TeV

Searches for semi-visible jets and invisibly decaying Higgs bosons

By

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Word count: number in words

Abstract

Here goes the abstract

Dedication and acknowledgements

This work is dedicated to my grandfather, Dato' Mahindar Singh Bhal, who was able to begin this journey with me but sadly unable to finish it.

There are far too many people and too little space to individually thank everyone who has accompanied me during this PhD, but I'll try my best.

Firstly, to my supervisor, Dr. Henning Flächer. Your advice and guidance over the course of this degree has been instrumental to achieving it, as well as encouraging my growth as a researcher.

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To my undergraduate cohort from Exeter. Though our meet ups are rare, I always look forward to our group holidays and hope they continue far into the future.

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Finally, and most importantly, my family deserve my thanks. You have been there for me since the very beginning supporting me through school, undergrad, PhD, and every other endeavour. To my grandparents, uncles, aunties, and cousins, my siblings Joe, Lydia, Sitara, and Arjen, my stepmum Nadia, and my cat Pixie, I am sincerely grateful to have you in my lives. But above all else, to my mum Meeta and dad Kiron, I could not have done any of this without you and as such, you have my deepest and most heartfelt love and gratitude.

Author's declaration

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's *Regulations and Code of Practice for Research Degree Programmes* and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

SIGNED: .... DATE: ....

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CHAPTER 1

Introduction

The universe, in all its vastness, structure, natural laws and chaos, is comprised of only three principal components: visible matter, the ingredients of stars, planets and life, is the only one we interact with on a regular basis; dark energy, a force or manifestation of something even more mysterious, responsible for the accelerating expansion of the universe, is almost entirely unknown; and dark matter, a substance invisible in all sense of the word, that binds galaxy together and influences large scale structure in the cosmos, is the topic of this thesis.

- Discuss dark matter: motivation, evidence for its existence (and why it can't be neutrinos/dead stars/interstellar debris, etc.), detection methods and how we can probe it at the LHC (production). Should most of this stuff go in the introduction instead?
- Briefly outline particle accelerators and their function, the fact that we can use them to potentially discover dark matter or infer more of its properties, and the models that will be discussed in more detail to try and achieve this outcome.
- The introduction probably doesn't need to be too long, maybe only a few pages. Compare length with other people's theses (ask Ben Krikler for a copy of his, look at Alex's and Lana's).

1.1 Section

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1.1.1 Subsection

Begins a subsection.

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Doing the same to check both sides of the paper (for when it's bound).

Also testing glossaries: pileup, Large Hadron Collider, LHC, Large Hadron Collider (LHC).

Also testing references: [7] (article), [9] (book), [8] (inproceedings), [1] (techreport).

Testing numbers: 1234567890 (normal), 1234567890 (math), 1234567890 (from siunitx).

Testing alphabet: The quick brown fox jumps over the lazy dog

Testing math characters compared to normal text: b-tag, b-tag, $\boldsymbol{b}$-tag, bbb$\mathrm{b}$$\boldsymbol{b}$b, $cccccc$.

Testing equations: $^1\!/\!_2\rho\Delta\phi\mathcal{L}$ (inline)

$$B(P) = \frac{\mu_0}{4\pi}\int\frac{I \times \hat{r}}{\bar{r}^2}\mathrm{d}r \text{ (equation environment)} \tag{1.1}$$

Testing symbols/macros: eV, MeV, GeV, TeV, p_{T}, $p_{\mathrm{T}}^{\mathrm{miss}}$, $E_{\mathrm{T}}^{\mathrm{miss}}$, H_{T}, $H_{\mathrm{T}}^{\mathrm{miss}}$, M_{T}, α_{dark}, r_{inv}, m_{χ}, $\mu\mu + \text{jets}$, $m_{\ell\ell}$, α_{T}, $t\bar{t} + \text{jets}$, $W(\rightarrow \ell\nu) + \text{jets}$, $\widetilde{\chi}_1^0$.

Chapter 2

Theory

This is the theory chapter.

- Give an overview of the fundamental forces and particles.
- Discuss the Standard Model in detail, emphasising certain aspects as they relate to dark matter and the Higgs field (and boson).
- Briefly recap dark matter, referencing descriptions in introduction.
- Discuss the theory behind combined Higgs to inv.: only SM process in which Higgs decays invisibly is $H \to ZZ \to 4\nu$ with branching ratio of 0.1 % [6], whilst the current observed experimental limit is 19 % from CMS [10] and 26 % from ATLAS [2]. If new, invisible particles couple to Higgs, branching ratio will be enhanced. Constraining $\mathcal{B}$ can also exclude some dark matter models.
- Discuss the theory behind the semi-visible jets analysis (main sources from Refs. [3, 4]): strongly interacting dark sector in Hidden Valley scenario with a portal to the visible sector. Mentioning dark quarks χ, dark confinement scale Λ_{dark}, dark hadronisation and decay, running coupling α_{dark}, etc.
- Explain some of the phenomenological/experimental event characteristics that overlap with both analyses, i.e., what a jet is, and maybe energy sums like $p_{\mathrm{T}}^{\mathrm{miss}}$, H_{T}, $H_{\mathrm{T}}^{\mathrm{miss}}$, etc.

2.1 The Standard Model

2.2 Limitations of the Standard Model

2.3 Dark matter

2.3.1 Measuring the branching ratio for the invisible decays of the Higgs boson

2.3.2 Searches for semi-visible jets

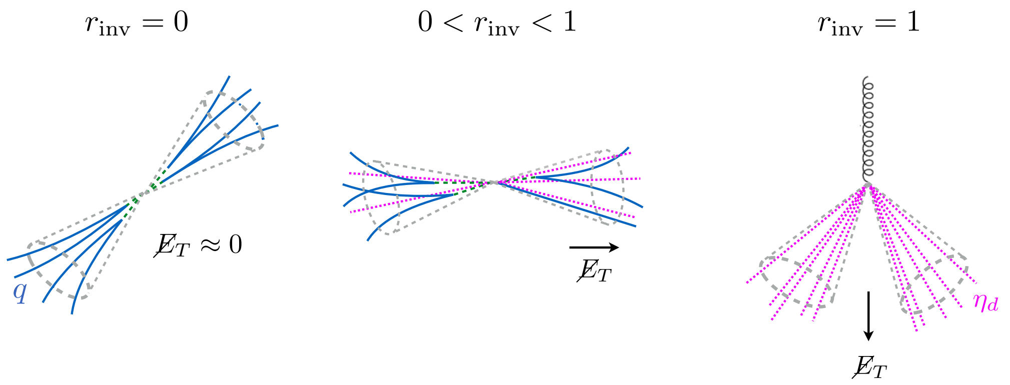


Figure 2.1: The typical direction of the missing transverse energy $\not{E}_{\rm T}$ (or $p_{\rm T}^{\rm miss}$) relative to the semi-visible jets as a function of their invisible fraction $r_{\rm inv}$ [4].

(a) s-channel

(b) t-channel

Figure 2.2: Example Feynman diagrams for the two main production modes of semi-visible jets [4]. A Z' boson mediates the s-channel process while a bifundamental Φ mediates the t-channel process.

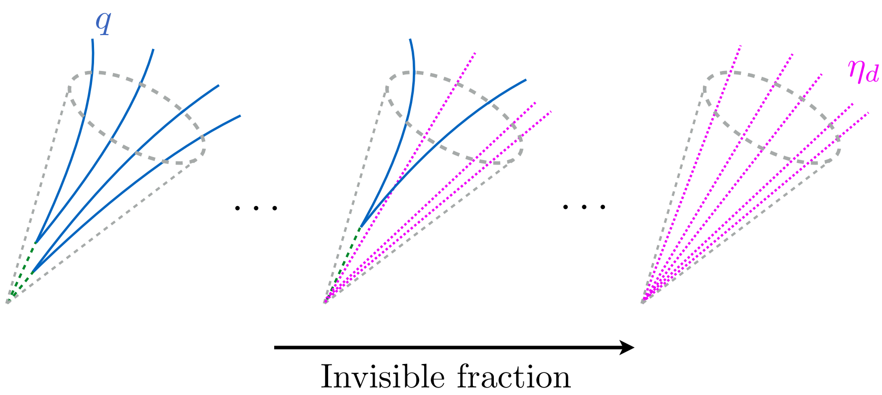


Figure 2.3: The constituents of a semi-visible jet as a function of its invisible fraction $r_{\rm inv}$ [4].

CHAPTER 3

The LHC and the CMS experiment

This is the detector chapter.

- Explain CERN and the LHC in more detail.
- Give an overview of the CMS experiment and detector (including all subsystems, object identification, algorithms for event/object reconstruction like Particle Flow and anti-k_T algorithm, and algorithms for tagging objects like b-jets).
- Either as a subsection in this chapter or in a separate chapter, discuss the Level-1 Trigger in depth. Emphasise the jet and energy sum triggers as I've worked on them, and Calorimeter Layer-2 for the same reason.

3.1 The Large Hadron Collider

Deep underground beneath the Franco-Swiss border lies the Large Hadron Collider (LHC), a synchrotron particle accelerator 27 km in circumference. Predominantly a proton collider, lead and xenon ions have also been injected for novel and unique studies. Four principle experiments are situated at their own interaction points where the two beams of particles are brought into contact: Compact Muon Solenoid (CMS), a general purpose detector with interests in precision measurements, searches for new physics, and many other avenues; ATLAS (A Toroidal LHC ApparatuS), another general purpose detector with similar aims to CMS; LHCb, designed to study the decay of B hadrons; and ALICE (A Large Ion Collider Experiment), primarily studying heavy ion collisions and the quark-gluon plasma.

The LHC began operating in 2010 at a centre of mass energy of $\sqrt{s} = 7$ TeV (teraelectron volts), 3.5 TeV per beam. A modest increase to 8 TeV was achieved by the end of Run-1 in 2013. After upgrades were performed, the LHC resumed operation in 2015, further pushing the frontiers of high energy physics with a centre of mass energy of $\sqrt{s} = 13$ TeV. While valuable data was taken, it was not until 2016 when Run-2 of the LHC began. This period ended in 2018 with 162.85 fb^{-1} of pp collisions delivered, 150.26 fb^{-1} of which were recorded by CMS.

3.2 The CMS experiment

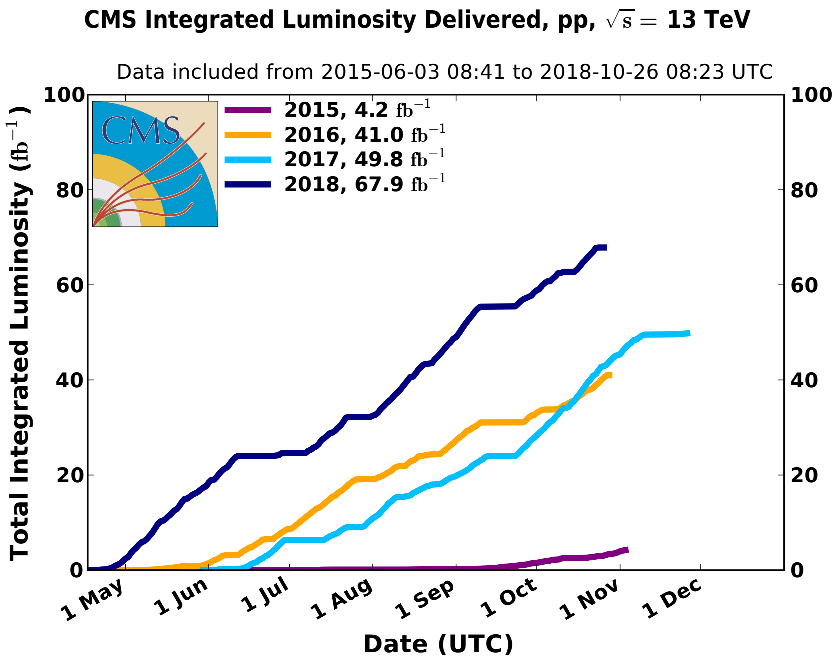


Figure 3.1: The integrated luminosity of pp collision data collected by CMS during 2015 and Run-2 of the LHC [5].

3.2.1 Jet energy corrections in the Level-1 Trigger

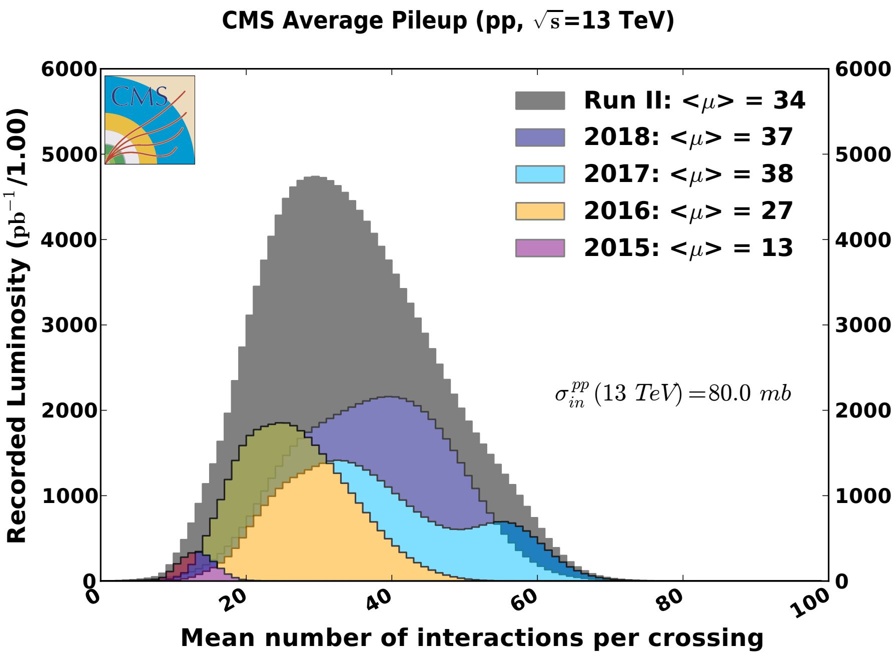


Figure 3.2: The average number of pileup interactions at CMS during 2015 and Run-2 of the LHC [5].

CHAPTER 4

Combined search for the invisible decay of the Higgs boson in hadronic channels

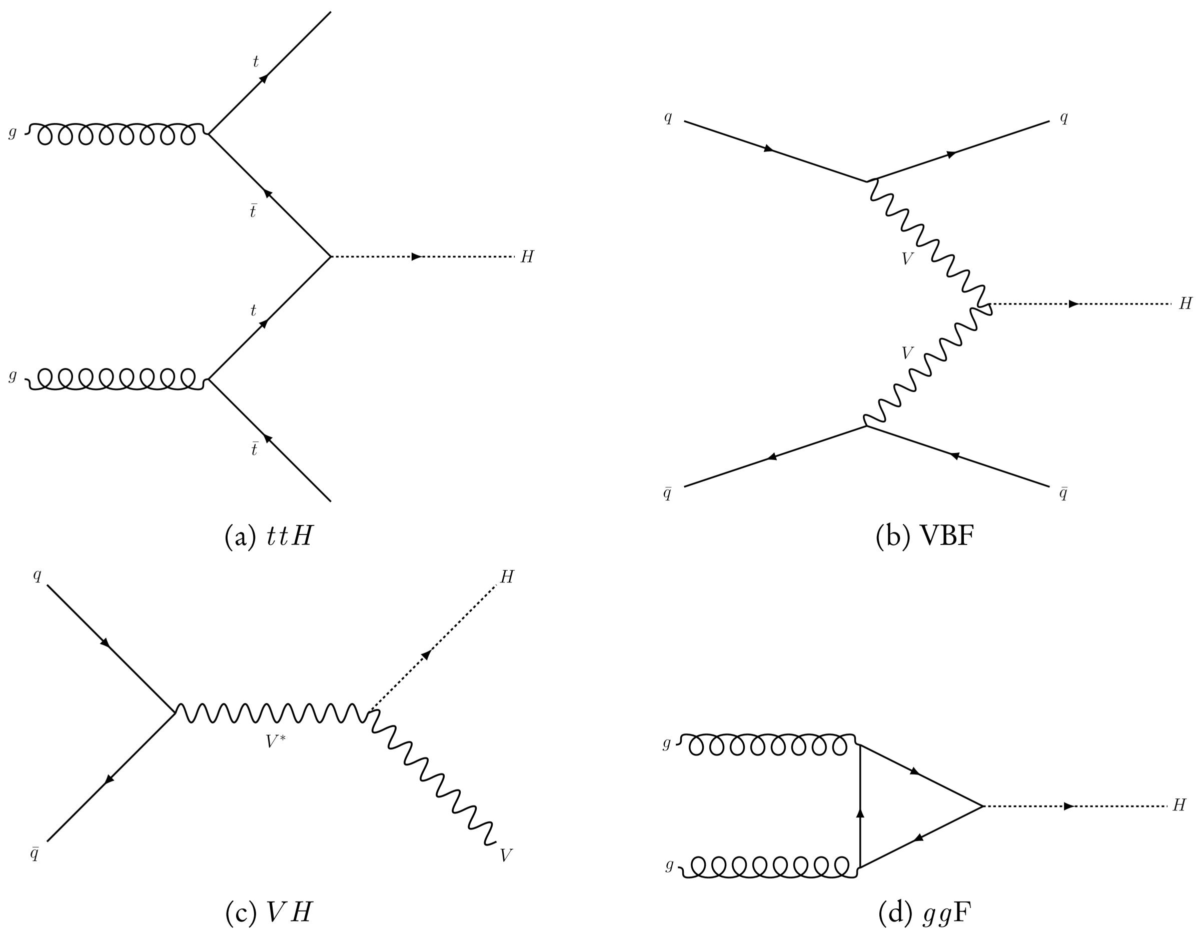
This is the analysis chapter on $H \to$ inv..

- Discuss how the theoretical aspects from the Theory chapter translate into an experimental search.
- Discuss the necessity of including all production modes of Higgs (invisible final state, so characterise events based on initial/additional particles). Also mention how sensitive each production mode is at contributing to the branching ratio limit. Emphasise the non-VBF modes (ggF, ttH, VH – W^+H, W^-H, ZH) in this chapter as that's what I've been working on and another student will be covering VBF.
- Talk about what makes this analysis unique: doing a combination over all production modes from the start instead of separate analyses combined at the end. Means we can share samples, systematics, background methods and workflows, build in orthogonality between the different modes and cover as much phase space as possible (with new final states such as boosted Z bosons with unresolved subjets). This makes the analysis much more cohesive and consistent.
- Include object definitions, overall analysis strategy, triggers, signal production (with each non-VBF mode in detail), event selection, background estimation and results/limit (including comparisons to previous results).
- Emphasise my contributions: control region construction and studies, background estimation, and other studies I will have conducted by the time I write up.

– Current material: no public plots as of yet. Hope to finish analysis by the time I begin writing up. We are preparing a CMS internal analysis note, documenting all aspects of the analysis. I will add all relevant information there which I can subsequently use when writing this chapter.

4.1 Analysis overview

4.1.1 Hadronic production modes of the Higgs boson



(a) ttH

(b) VBF

(c) VH

(d) ggF

Figure 4.1: The Feynman diagrams for the four main hadronic production modes of the Higgs boson.

4.2 Data and simulation

4.3 Triggers

4.4 Categorisation of the non-VBF production modes

4.5 Background estimation

4.5.1 Control regions

4.5.2 Background estimation methods

CHAPTER 5

SEARCH FOR DARK MATTER THROUGH THE PRODUCTION OF SEMI-VISIBLE JETS

This is the analysis chapter on semi-visible jets.

- Discuss how the theoretical aspects from the Theory chapter translate into an experimental search.

- Include object definitions, triggers, overall analysis strategy, signal production, event selection, background estimation and results/limit (including comparisons to similar searches – monojet/dijet exotic searches).

- Emphasise my contributions: s- and t-channel signal model production and understanding. Angular variable study for QCD background rejection (if used).

- Current material: no public plots as of yet. Hope to finish s-channel analysis soon (see previous section for caveats regarding inclusion), no timeline on t-channel analysis.

5.1 Analysis overview

5.2 Data and simulation

5.2.1 Generating signal samples in PYTHIA

5.2.2 Generating signal samples in MadGraph

5.2.3 Triggers

5.3 Background estimation

Chapter 6

Conclusions

This is the conclusion.

- Include a summary of thesis and work done over the course of my PhD with emphasis on the most important results/contributions.
- Mention the direction the semi-visible jet and Higgs to invisible analyses can take (sharing ideas/strategies I have, potential improvements with more LHC data and future prospects from potential future experiments).

APPENDIX A

Appendix A

Begins an appendix

Bibliography

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Glossary

***b*-jet** A jet identified by a given algorithm or classifier as originating from a b quark.

anti-k_{T} algorithm .

pileup The term ascribed to additional proton-proton collisions during a bunch crossing. Pileup interactions typically produce a large number of low-momentum particles.

semi-visible jet A shower of Standard Model and dark hadrons from the decay of a leptophobic Z' or Φ mediator that couples the hidden sector to the standard model.

Acronyms

ALICE A Large Ion Collider Experiment.

ATLAS A Toroidal LHC ApparatuS.

CERN Organisation Européenne pour la Recherche Nucléaire/European Organisation for Nuclear Research.

CMS Compact Muon Solenoid.

LHC Large Hadron Collider.

QCD Quantum Chromodynamics.

SM standard model.

TeV teraelectron volt.

VBF vector boson fusion.